

## SYNTHESIS OF N-VINYL FORMAMIDE

### CROSS-REFERENCE TO RELATED APPLICATION

The present application is a continuation in part application of U.S. Patent Application Serial No. 10/652,104, filed August 29, 2003, which claims benefit of U.S. Provisional Patent Application Serial No. 60/407,077, filed August 30, 2002, the disclosures of which are incorporate herein by reference.

### BACKGROUND OF THE INVENTION

[0001] The present invention relates to the synthesis of N-vinylformamide, and particularly, to the synthesis of N-vinylformamide using cyclic anhydride reagents.

[0002] N-vinylformamide (NVF) is a monomer with potentially useful properties in that it free-radically polymerizes to produce water-soluble poly(N-vinylformamide) (PNVF) and also undergoes controlled radical polymerization using RAFT methodology. Badesso, R. J.; Nordquist, A. F.; Pinschmidt, Jr. R. K.; and Sagl, D. J. "Hydrophilic polymers: performance with Environmental Acceptance", Glass, E.; Ed.; America Chemical Society, Washington, DC, 1995, p489. PNVF is probably the most practical precursor for preparation of poly(vinylamine). Because vinyl amine is unstable and hence cannot be maintained, PNVF is likely the best route to the generation of polyvinyl amine, a useful and less toxic alternative to polyacrylamide and other cationic, water-soluble polymers. PNVF is easily hydrolyzed under basic or acidic conditions to form poly(vinylamine).

[0003] There are three known commercial routes to NVF. For example, BASF, at its Ludwigshafen, Germany site, reacts acetaldehyde with HCN, then formamide, forming the cyanoethyl formamide (FAN). FAN is then "cracked" to NVF plus HCN, where the latter is recycled. The BASF Ludwigshafen, Germany site is one of the few sites in the world skilled in HCN chemistry. As this highly toxic chemical cannot be transported, the process is most likely restricted to Ludwigshafen.

[0004] Mitsubishi developed a process whereby acetaldehyde is reacted with formamide to form hydroxyethyl formamide (HEF) using either acid or base catalysis. HEF is then reacted with methanol to form methoxyethyl formamide (MEF) using an acid catalyst with the loss of water. HEF is finally cracked to methanol and NVF, and the NVF purified. It has been reported that the NVF material synthesized by this method, exhibited lower than desired purity.

[0005] Air Products developed an alternative route to NVF wherein HEF is reacted with additional formamide (over a solid acid catalyst) to form the ethylidene bisformamide (BIS) plus water. BIS is then cracked (pyrolyzed) to form NVF plus formamide (wherein the latter is recycled). The NVF is then vacuum distilled. It is quite important in the operation of this process to minimize the hydrolysis of formamide (creating ammonia that fouls the catalyst) during BIS formation. Obviously the presence of water during this reaction creates problems.

[0006] It is very desirable to develop alternative routes to the synthesis of N-vinylformamide.

#### SUMMARY OF THE INVENTION

[0007] In one aspect, the present invention provides a process to produce N-vinylformamide including the steps of: reacting hydroxyethyl formamide with a reactant including at least one cyclic anhydride group to form an ester, and dissociating (or cracking) the ester to synthesize N-vinylformamide and a compound including at least one diacid group. The ester can be dissociated using heat. The reactant including at least one cyclic anhydride group can, for example, be succinic anhydride, maleic anhydride, phthalic anhydride, (2-dodecen-1-yl)succinic anhydride, *exo*-3,6-epoxy-1,2,3,6-tetrahydrophthalic anhydride, a polymer including at least one cyclic anhydride group, or a solid support to which at least one cyclic anhydride group is covalently tethered. Preferably, the cyclic anhydride is regenerated from the diacid formed in the synthesis of the ester. The anhydride can, for example, be regenerated by heating the diacid to dehydrate the diacid or by passing the diacid over a dehydration catalyst. Homogeneous or heterogeneous dehydration catalysts can be used (for example, zeolite, resins acids, vanadium oxide, phosphoric oxide or any other dehydration catalyst as known to those skilled in the art). The conditions required to dehydrate diacid groups are preferably different from the conditions used to dissociate the ester. For example, in the case that heat is used to dehydrate the diacid, the temperature required for dehydration can be higher than the temperature used to dissociate the ester.

[0008] As used herein, the term "polymer" refers to a compound having multiple repeat units (or monomer units) and includes the term "oligomer," which is a polymer that has only a few repeat units. The term polymer also includes copolymers which is a polymer including two or more dissimilar repeat units (including terpolymers - comprising three dissimilar repeat units - etc.).

[0009] Although the reaction can be carried out without the use of solvent, a solvent can be added. Suitable solvents include aprotic or aromatic solvents. Preferably, such solvents do not interfere with the reactions of the present invention. NVF can be used as a solvent in the process. Examples of other suitable solvents include, but are not limited to, toluene, xylene, acetonitrile, ether, dimethyl sulfoxide and/or acetaldehyde. Suitable solvents also include isoparaffin-like solvents, including, but not limited to, the products sold by Exxon Corporation under the name ISOPAR®, which are generally non-toxic in nature.

[0010] In one embodiment a solvent (for example, NVF) is used in which NVF is soluble and in which a polymer including at least one cyclic anhydride group is at least partially soluble. However, the polymer including at least one ester group formed in the synthesis and the polymer including at least one diacid group formed in the synthesis have no or limited solubility in the solvent.

[0011] Generally, polymers used in the process of the present invention preferably include or incorporate a plurality of cyclic anhydride groups. For example, a copolymer of methyl vinyl ether and maleic anhydride can be used. The methyl vinyl ether/maleic anhydride copolymer can, for example, have a weight average molecular weight in the range of approximately 190,000 to 3,000,000. The polymer can also be a reaction product of an alpha olefin or a mixture of alpha olefins with maleic anhydride. In one embodiment, the alpha olefin is a C-18 alpha olefin and the copolymer has a molecular weight of at least 20,000. The polymer can also be a methyl vinyl ether/ maleic anhydride/ decadiene copolymer. Another suitable polymer for use in the present invention is a copolymer of styrene and maleic anhydride. The styrene/maleic anhydride copolymer can, for example, have a weight average molecular weight of at least 2000.

[0012] In one embodiment the polymer is a solid in the reaction. For example, the polymer can be a porous crosslinked solid. Preferably, the porous polymer has a relatively high surface area.

[0013] In one embodiment, in which the reactant including at least one cyclic anhydride group is a solid support to which at least one cyclic anhydride group is covalently tethered, the solid support is silica.

[0014] In another embodiment, acetaldehyde, formamide and the reactant including at least one cyclic anhydride group are mixed in a single reaction vessel, wherein hydroxyethyl formamide is formed in the reaction vessel to react with the reactant including at least one cyclic anhydride group.

[0015] In another aspect, the present invention provides a process to produce N-vinylformamide including the steps of: reacting hydroxyethyl formamide with a reactant including at least one cyclic anhydride group to form an ester, and dissociating the ester via heat in a thin film evaporation to synthesize N-vinylformamide and a compound including at least one diacid group, the N-vinylformamide separating from the diacid during the thin film evaporation.

[0016] In another aspect, the present invention provides a process to produce N-vinylformamide including the step of: mixing acetaldehyde, formamide and a source of anhydride in a single reaction vessel. It is believed that the anhydride reacts with hydroxyethyl formamide formed in the reaction vessel to form an ester as described above. The ester is dissociated (or cracked) as described above to synthesize N-vinylformamide and a compound including at least one diacid group. In one embodiment, the source of anhydride is a reactant including at least one cyclic anhydride group. The reactant including at least one cyclic anhydride group can, for example, be succinic anhydride, maleic anhydride, phthalic anhydride, a polymer including at least one cyclic anhydride group, or a solid support to which at least one cyclic anhydride group is covalently tethered. In one embodiment, the acetaldehyde to formamide mole ratio can, for example, be at least two. However, lower acetaldehyde to formamide mole ratios can be used. An acid or base catalyst can be used in the reaction to make hydroxyethyl formamide.

[0017] The process of the present invention can be carried out continuously or batchwise. Suitable reactors include, but are not limited to, tubular reactors and stirred tank reactors.

[0018] In a further aspect, the present invention provides a process to produce N-vinylformamide including the steps of: mixing acetaldehyde, formamide and a source of anhydride in a single reaction vessel, reacting the acetaldehyde, formamide and the source of anhydride in the reaction vessel under pressure, dissociating an ester formed by a reaction between the source of anhydride and hydroxyethyl formamide formed in the reaction vessel to synthesize N-vinylformamide and a compound including at least one diacid group. Once again, it is believed that the acetaldehyde and the formamide react to form HEF and that HEF reacts with the source of anhydride to form the ester. In general, performing the reaction in a pressurized vessel prevents loss of relatively volatile acetaldehyde, particularly at elevated temperatures.

[0019] In still another aspect, the present invention provides a reagent including at least one cyclic anhydride group covalently tethered to a solid support. The solid support can, for example, be silica. Preferably, a plurality of cyclic anhydride groups are tethered to the solid support.

[0020] The present invention, along with the attributes and attendant advantages thereof, will best be appreciated and understood in view of the following detailed description taken in conjunction with the accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0021] Figure 1 illustrates the sequential synthesis of NVF via first synthesizing HEF. reacting HEF with acetic anhydride and cracking the resulting ester to form NVF.

[0022] Figure 2 illustrates a one pot synthesis of NVF of the present invention wherein acetaldehyde, formamide and acetic anhydride are mixed.

[0023] Figure 3A illustrates an embodiment of a synthetic route to NVF of the present invention wherein a cyclic anhydride (several suitable cyclic anhydrides are set forth) is reacted with HEF to form an HEF-adduct, which is subsequently cracked to form NVF.

[0024] Figure 3B illustrates a sequential synthesis under the general synthetic route of Figure 3A.

[0025] Figure 3C illustrates a one-pot synthesis under the general synthetic route of Figure 3A.

[0026] Figure 4 illustrates an embodiment of a synthetic route of the present invention in which a poly(styrene-co-maleic anhydride) copolymer is reacted with HEF.

[0027] Figure 5A illustrates a cyclic anhydride covalently tethered to a solid support for use in the synthetic methods of the present invention.

[0028] Figure 5B illustrates one embodiment of a synthetic route to the synthesis of a silica supported cyclic anhydride.

[0029] Figure 6 illustrates a schematic representation of a process for synthesis of NVF from a cyclic anhydride in which the HEF-adduct is cracked and NVF separated in a thin film evaporator.

## DETAILED DESCRIPTION OF THE INVENTION

[0030] Figure 1 illustrates a sequential synthesis of NVF developed at Air Product wherein HEF is first synthesized via the reaction of acetaldehyde and formamide. See Parris, G.E. and Armor, J.N, Applied Catalysis, Vol. 78, pp 65-78 (1991). HEF is then reacted with acetic anhydride to form an HEF adduct. The resulting HEF adduct/ester is subjected to heat (cracked) to form NVF.

[0031] The present inventors have discovered that NVF can also be formed via a single reaction mixture including acetaldehyde, formamide and an anhydride such as acetic anhydride as illustrated in Figure 2. The resulting HEF adduct is cracked to form NVF. The one-pot or single reactor synthesis of the present invention can, for example, provide cost savings by reducing unit operation costs. As expected from studies of the sequential synthetic route, the reaction rate increased in the one-pot synthesis with increasing temperature. As monitored by IR, for example, the anhydride peak was found to disappear in 42 hours at room temperature (approximately 22°C), in 23 hours at 50°C, and in 7.5 hours at 100°C, in the sequential synthesis. IR analysis of a one-pot synthesis according to Figure 2 also demonstrated disappearance of the anhydride peak over time. The temperature of the reaction of the present invention is generally approximately 0°C to 150°C, preferably approximately 20°C to 100°C, and more preferably approximately 30 to 80°C. In the studies of the present invention, a reaction temperature in the range of approximately 30°C to approximately 80°C was used.

[0032] Preferably, the reaction takes place under pressure (that is, in a reaction vessel at a pressure greater than atmospheric pressure). In that regard, the acetaldehyde is volatile and can vaporize from the reaction mixture, particularly at elevated temperatures. Loss of acetaldehyde is particularly undesirable as the reaction between acetaldehyde and formamide is an equilibrium reaction. Reacting the one-pot synthesis in a pressurized reaction vessel eliminates this concern. In a number of reactions of the present invention using succinic anhydride, for example, the reaction occurred at approximately 50°C and at a pressure in the range of approximately 50 to approximately 100 psi.

[0033] Either an acid catalyst or a base catalyst can be used. If an acid catalyst is used, only a catalytic amount of acid is preferably added to the reaction mixture (for example, 0.001 – 0.2 times the stoichiometry to HEF). Example of suitable acid catalysts include, but are not limited to, sulfuric acid, paratoluenesulfonic acid, methane sulfonic acid, amberlyst or any other acidic ion exchange resin. If a base catalyst is used, a nearly stoichiometric amount

of base can be required (for example, 0.2 to 5 times the stoichiometry to HEF). Suitable homogeneous catalyst for use in the present invention include, but are not limited to, triethylamine, pyridine and caustic catalysts. In general, any basic ion exchange catalyst such as Amberlite, Lewatit, Puralit is also suitable. Basic zeolites can also be suitable in certain cases.

**[0034]** In each of the synthetic routes of Figure 1 and 2, however, two moles of acetic acid are produced during the synthesis of one mole of NVF. One mole of acetic acid is produced in the synthesis of the HEF adduct, and another mole of acetic acid is produced during cracking of the HEF adduct. Acids such as acetic acid destabilize NVF. Moreover, the removal of such acids via, for example, distillation is difficult as the relative volatilities of the acid and NVF are similar.

**[0035]** In another aspect of the present invention as illustrated, for example, in Figures 3A through 3C, an alternative route to the synthesis of NVF is provided in which a cyclic anhydride is reacted with HEF. In the synthetic route of the present invention, HEF is reacted with a cyclic anhydride to form the corresponding ester (HEF adduct). The ester is then cracked to NVF plus the corresponding diacid under very mild conditions (for example, temperatures in the range of approximately 25°C to approximately 250°C). The temperature of cracking is generally approximately 0°C to 250°C, preferably approximately 20°C to 200°C, and more preferably approximately 60 to 180°C.

**[0036]** While one can form NVF from a simple, non-cyclic anhydride (for example, acetic anhydride as illustrated in Figures 1 and 2), this reaction produces a very soluble acid byproduct which ultimately destabilizes the NVF as described above. Once again, the removal or separation of the resultant acids using non-cyclic anhydrides is very difficult. In the synthetic route of the present invention, relatively heavy cyclic anhydrides (many of which are commercially available or readily synthesized from commercially available reagents) are reacted with HEF to produce the corresponding HEF adduct and a diacid. No byproduct is produced. The diacid generated during the cracking step is generally less soluble than, for example, acetic acid formed in the synthetic route of Figures 1 and 2. Indeed, in several embodiments of the present invention in which a solubilized source of cyclic anhydride is used, the diacid may precipitate as a solid as it is formed. Examples of cyclic anhydrides suitable for use in the synthetic processes of the present invention include maleic anhydride, succinic anhydride, phthalic anhydride, 2-dodecen-1-yl)succinic anhydride,

and *exo*-3,6-epoxy-1,2,3,6-tetrahydrophthalic anhydride (the structures of which are set forth in Figure 3A).

[0037] The diacid formed in the synthesis of the present invention can be recycled and dehydrated to reform the anhydride. This recycling dehydration step can generally occur at a temperature higher than the temperature used to crack the HEF adduct and results in the formation of water. The temperature of the dehydration is generally approximately 100°C to 450°C, preferably approximately 120°C to 300°C, and more preferably approximately 150 to 250°C. A dehydration catalyst can also be used to lower the temperature of dehydration, but is preferably not present in the cracking step to avoid the undesirable formation of water when NVF is formed. Suitable dehydration catalysts include homogeneous and heterogeneous catalysts (for example, zeolite, resins, acids, vanadium oxide, phosphoric oxide and any other dehydration catalyst as known to those skilled in the art). Unlike several current synthetic routes to NVF, the water produced in the recycling step of the present invention is formed “offline” and will not result in hydrolysis of the formamide precursor or the NVF product. Moreover, the synthetic route of the present invention requires less stringent conditions than current synthetic routes and hence can provide a product of increased purity. NVF of increased purity, for example, allows for generation of higher molecular weight poly(NVF)).

[0038] Various “substituted” cyclic anhydrides can be used in the synthetic route of the present invention to further decrease any adverse effects upon the NVF product of the diacid produced in the synthesis of the present invention. Generally, the use of such substituted cyclic anhydrides preferably simplifies or facilitates the separation of the substituted cyclic anhydride (as compared to the unsubstituted cyclic anhydride) from the NVF product. For example, use of a substituted cyclic anhydride can reduce the solubility of the resulting diacid in the process solvent and/or otherwise facilitate the separation of that diacid from the NVF product. For example, in one embodiment a polymeric material including cyclic anhydride groups can be reacted with HEF. In the embodiment of Figure 4, for example, a copolymer of styrene and maleic anhydride was used as the source of cyclic anhydride. In this embodiment, the cracking reaction produced liquid NVF and generally insoluble or reduced solubility polymer including diacid groups.

[0039] Polymers including cyclic anhydride groups for use in the present invention can be soluble in a solvent in which the reaction is carried out. As HEF is a solid at room temperature, the adduct of HEF and the anhydrides used in the present invention may in some



cases also be a solid. Thus, the use of a solvent/co-solvent may be required. As any solvent used in the processes of the present invention is typically ultimately required to be separated from the NVF product, it is advantageous to use NVF as a process solvent in the reactions of the present invention. In using NVF as the process solvent, a recycle stream can be taken from an intermediate point in the process to provide the needed solvent. In the case that a soluble polymer including cyclic anhydride groups are used, the resulting polymer containing diacid groups preferably readily precipitates from solution (for example, upon formation or upon addition of a co-solvent or other additive) and/or is preferably readily otherwise separable from the NVF product. Separation of the polymer including diacid groups from NVF is typically readily achieved given the substantial difference in molecular weight between NVF and the polymer including diacid groups.

[0040] Because of the great difference in the volatilities of the diacid and NVF, it is possible, for example, to separate the NVF monomer by a short residence time flash stripping leading to an enhanced quality of monomer. Conditions of cracking (temperature and vacuum) can also be adjusted to flash the monomer as soon as it is formed.

[0041] Thin film evaporation techniques such as wipe or wiped film evaporation or falling film evaporation are suitable for both cracking the HEF adduct and separating NVF from the resulting diacid. Figure 6 illustrates schematically one embodiment of a process for synthesis of NVF of the present invention in which the HEF adduct is cracked and NVF separated using a thin film evaporator. Thin film evaporation techniques are characterized by short residence times, enabling separation of the NVF monomer from the diacid before significant destabilization of the NVF can occur.

[0042] In one embodiment, the reaction mixture including the HEF-adduct is fed to a falling film evaporator. In a typical falling film evaporator, liquid is evaporated as it flows downward in a film on the inner side of heated tubes. Thus, liquid and vapors flow downward in parallel flow. The gravity induced downward movement is increasingly augmented by concurrent vapor flow. As clear to one of ordinary skill in the art, the number of tubes, the length of the tubes and the diameter of the tubes in the falling film evaporator determines the overall surface area for the formation of the film and the rate at which the relatively volatile NVF is removed. One of ordinary skill in the art can readily determine the surface area of the falling film evaporator for a desired flow rate of the process stream in a continuous process. The NVF product can, for example, be taken overhead to a condenser, wherein the NVF is condensed.

[0043] Preferably, the falling film evaporator is maintained at a reduced pressure of less than about 760 mm Hg (about 14.7 psi), more preferably less than about 100 mmHg (about 1.93 psi) and even more preferably less than about 30 mm Hg (about 0.58 psi). The temperature of the material (for example, oil) heating the tubes of the falling film evaporator is preferably in the range of approximately 50 to 400°C, more preferably in the range of approximately 120 to 300°C and, even more preferably, in the range of approximately 160 to 250°C.

[0044] In another embodiment, the reaction product mixture including the HEF adduct is fed to a wiped film evaporator. Like falling film evaporators, wiped film evaporators are well-established separation process units wherein substances of lower boiling points are removed from a liquid stream of a higher boiling point. Typically, a wiped film evaporator includes a vertical cylindrical shell, surrounded by a heating jacket, which forms the heat treatment zone. Above the heat treatment zone there is an outlet for the vapors exit the unit. At the bottom end of the unit there is an outlet for the remaining liquid stream. A set of wiper blades is typically mounted on the shaft which rotates with a fixed angular velocity. The blades lay out a thin film on the wall of the cylindrical shell. The film formed on the wall of the evaporator is usually thicker than the clearance between the wiper blades and the wall. As the blade moves, a fillet of liquid or "bow wave" is created on its front edge.

[0045] Preferably, the falling film evaporator is maintained at a reduced pressure of less than about 760 mm Hg (about 14.7 psi), more preferably less than about 100 mm Hg (about 1.93 psi) and even more preferably less than about 30 mm Hg (about 0.58 psi). The temperature of the heating zone of the wiped film evaporator is preferably in the range of approximately 50 to 400°C, more preferably in the range of approximately 120 to 300°C and, even more preferably, in the range of approximately 160 to 250°C.

[0046] If a solid HEF ester adduct is formed in the reaction of the present invention, the solid ester adduct can be heated at, for example, 150°C and 2mm Hg, and NVF will naturally be formed in a gaseous state. The gaseous NVF can be condensed as pure NVF in another vessel. Melt crystallization can also be used to separate the monomer from a third solvent used to remove the diacid.

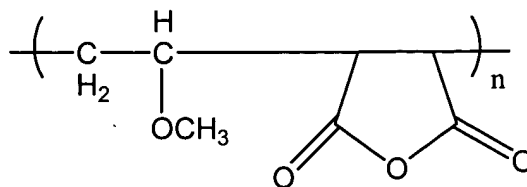
[0047] Additionally, polymers including cyclic anhydride groups that are insoluble in the process solvent (for example, solid polymers) can also be used in the present invention. As reactions of HEF with such insoluble polymers will occur only at the surface of the

polymer, the surface area of such polymer is preferably relatively high. Such polymers can, for example, be synthesized as porous polymeric beads in a manner similar to the synthesis of, for example, polymeric ionic exchange beads as known in the art. In one embodiment, for example, divinyl benzene can be used as a crosslinker in a copolymer of divinyl benzene, styrene and maleic anhydride to produce a high surface area, porous polymer bead including cyclic anhydride groups for use in the reactions of the present invention. Preferably, the surface area is maximized. A surface area of, for example, at least 10 m<sup>2</sup>/g is preferred. As the resulting diacid is covalently bound to the solid polymer, the detrimental effect of the diacid groups upon the NVF product is not substantial.

[0048] As illustrated in, for example, Figure 5A, in another embodiment of the present invention, cyclic anhydride reagents for use the present invention can be immobilized upon a solid support (for example, a polymeric bead or a silica support). Figure 5B illustrates one embodiment of immobilization of a cyclic anhydride group on silica. Supports other than silica (for example, glass, alumina and activated carbon can also be used to immobilize the cyclic anhydride reagents of the present invention.

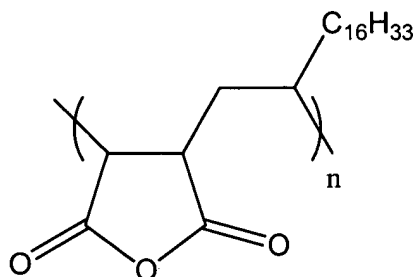
[0049] The cyclic anhydrides of the present invention can be reacted in either a sequential synthesis or a one-pot synthesis to form NVF as described above. In the generalized formula of a cyclic anhydride suitable for use in the present invention, R<sup>1</sup> and R<sup>2</sup> can independently be chosen from a very broad range of substituents. It is believed that electron withdrawing groups (for example, NO<sub>2</sub>, halo group (for example, Cl, F or Br) and -CN) may result in a faster reaction time. In the case that a polymer including or incorporating cyclic anhydride groups is used, R<sup>1</sup> and R<sup>2</sup> can, for example, be styrene or vinyl repeat groups. Virtually any vinyl monomer (for example, vinyl ether) is suitable for use in synthesizing polymers suitable for use in the present invention. Maleic anhydride typically copolymerizes in an alternative fashion. Thus R<sup>1</sup> and R<sup>2</sup> can be the same in the case of copolymerization of maleic anhydride. Styrene is an attractive comonomer as formation of crosslinked porous beads is readily achieved using styrene as a comonomer.

[0050] A number of polymeric anhydrides suitable for use in the present invention are commercially available. For example, a methyl vinyl ether/maleic anhydride copolymer is available from ISP Chemicals under the name GANTREZ® in the molecular weight range of 190,000 to 3,000,000. The polymer has the general formula:



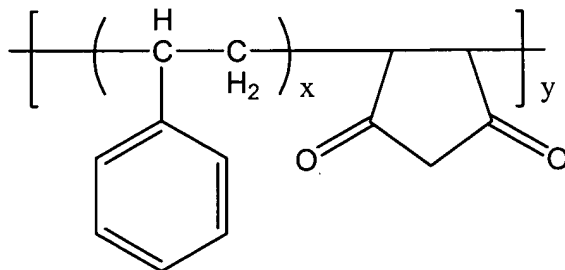
A methyl vinyl ether/maleic anhydride decadiene crosslinked polymer is also available from ISP Chemicals under the name STABILEZE®.

[0051] A copolymer of a C-18 alpha olefin with maleic anhydride have the following formula:



is available from Chevron Phillips under the produce name PA-18 Polyanhydride Resin.

[0052] Styrene maleic anhydride copolymers having the general formula:



are available, for example, from Sartomer of Exton, PA.

### [0053] Experimental Examples

[0054] In the studies of the present invention, some of the quantities were varied between experiments but the quantities set forth in the examples below are representative values and scales. No attempt was made to optimize any of the reactions studied.

[0055] **Example 1. Synthesis of HEF**. The first step in the two-step or sequential reaction of the present invention is the synthesis of HEF. Typically, 0.35ml triethylamine (0.0025mol), 10ml formamide (0.25mol) and 20ml isooctane were placed in a flask fitted with a cold-finger condenser. Acetaldehyde was slowly added to the formamide layer (lower) over several hours (~4h) until a white suspension (HEF) was formed. The HEF was then collected by filtration and washed with isooctane. This reaction is an equilibrium reaction and care was taken with the HEF to avoid decomposition back to formamide and

acetaldehyde. Generally, the HEF was used in further reactions the same day it was synthesized.

[0056] **Example 2. Reaction of HEF with succinic anhydride.** 4.59g succinic anhydride (0.046mol) in 100ml ethyl acetate was added to 4g HEF (0.045mol) in 100ml ethyl acetate containing 5mg Amberlyst 15 acid catalyst. The solution was stirred at 50°C for 24h before filtering out the catalyst and removing the solvent under vacuum to yield a white solid. The product was washed with dichloromethane and dried in air. NMR analysis showed the presence of a carboxylic acid proton (12.1ppm), which indicates ring opening of the anhydride.

[0057] **Example 3. Reaction of HEF with Phthalic Anhydride.** The method described in Example 2 was also been used to react phthalic anhydride (6.81g; 0.046mol) with HEF. The reaction yielded a white solid reaction product. NMR analysis showed the carboxylic acid proton associated with ring-opening of the anhydride.

[0058] **Example 4. Dehydration of HEF-Anhydride Adduct.**

[0059] **Example 4A. Thermal Gravimetric Analysis Studies.** Samples taken from the HEF-anhydride adduct were heated in a Thermal Gravimetric Analysis (TGA) machine at various temperatures under a flow of nitrogen to produce NVF and the dicarboxylic acid. The NVF vapor pressure caused it to be separated from the diacid by the flow of N<sub>2</sub>.

[0060] Samples of the HEF-succinic anhydride adduct were held at different temperatures and their weights recorded over time. The observed weight loss was compared to the theoretical weight loss expected from the elimination of NVF from the adduct (to leave succinic acid). The theoretical maximum weight loss resulting from the elimination of NVF is 37.38%. The results are shown in Table 1.

Table 1.

Temperature/°C	Start weight/mg	End weight/mg	Weight loss/mg	Weight loss %
100	11.5	0.8	10.7	93.0
90	11.13	7.97	3.16	28.4
80	9.90	7.41	2.49	25.2
70	10.58	8.74	1.84	17.4

[0061] At 100°C the weight loss was greater than expected from the formation and removal of NVF, indicating that the diacid may have also been volatilized. At 80°C or below

the weight loss is less than the theoretical maximum, but TGA plots indicated that further weight loss would occur over a longer time period.

[0062] The remains of the TGA samples were analyzed by nuclear magnetic resonance (NMR). For the sample heated to 80°C the remaining material was shown to be succinic acid. The same was true of the remains from the 70°C and the 60°C TGA experiments, but as the temperature is decreased there is a slight increase in impurity (that is, remaining HEF-anhydride adduct or NVF). This result is consistent with slower reaction rates and slower removal of NVF from the sample pan at the lower temperatures studied.

[0063] **Example 4B. Gas Chromatography Studies.** In addition to the TGA analysis, a sample of the HEF-anhydride adduct was analyzed by gas chromatography (GC). The heat of the injector or columns on the GC machine cracked or split the adduct into the diacid and NVF. The GC trace of the adduct showed a peak that matched the peak from an NVF standard. These results support the results of TGA analysis in demonstrating that NVF is produced upon heating the adduct.

[0064] **Example 5. Production of NVF using poly(styrene-co-maleic anhydride).** Acetaldehyde [5.66ml; 0.10mol] was dissolved in dioxane [20ml] at 10°C. Formamide [01ml; 0.025mol; containing 0.5mol% K<sub>2</sub>CO<sub>3</sub>] was added dropwise, and the reaction was stirred at 10-15°C for 2h. Poly(styrene-co-maleic anhydride) [68wt% styrene; Mn~1700] [8.29g] was dissolved in dioxane [50ml] and the solution added to the reaction. IR monitoring was done throughout the reaction. Anhydride peaks substantially reduced but did not completely disappear in IR over the time the reaction was carried out. Synthesis of NVF was confirmed by NMR.

[0065] **Example 6. One-pot reaction of acetaldehyde, formamide and acetic anhydride**

[0066] **Example 6A. No solvent:** Acetaldehyde [21ml; 0.377mol], formamide [5ml; 0.126mol; containing 0.5mol% K<sub>2</sub>CO<sub>3</sub>] and acetic anhydride [6ml; 0.062mol] were added to a flask and stirred at approximately 10°C for 2h. The reaction was allowed to warm to room temperature over 1h and then heated to 70°C. IR monitoring was done throughout, demonstrating disappearance of the anhydride peaks and indicating the synthesis of the HEF adduct.

[0067] **Example 6B. With solvent:** The same method as i) was followed but in addition, 40ml of isooctane was added at the start of the reaction. Two layers were present

throughout the reaction. IR monitoring was done throughout, demonstrating disappearance of the anhydride peaks and indicating the synthesis of the HEF adduct.

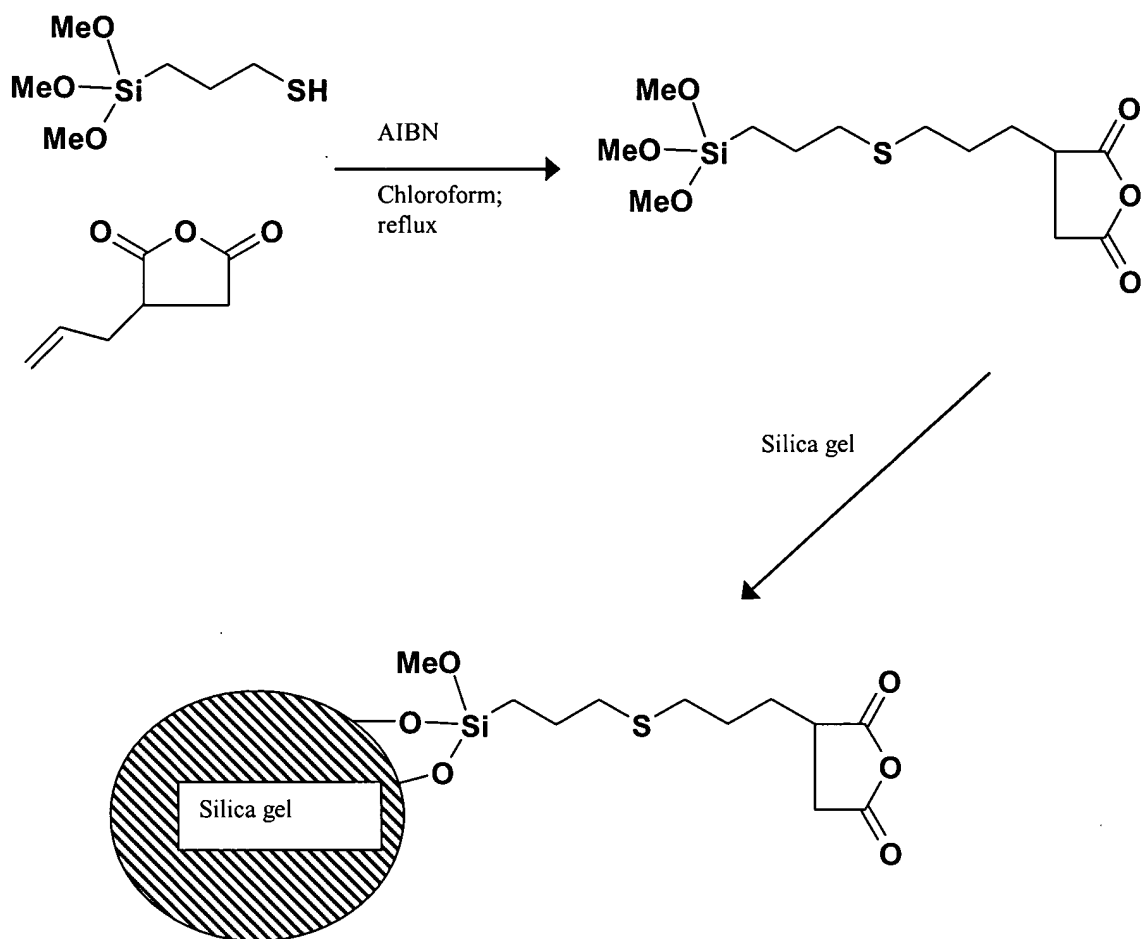
[0068] **Example 7. One-pot reaction of acetaldehyde, formamide and succinic anhydride under pressure.** The low boiling point (21°C) of acetaldehyde causes difficulties as the reaction between HEF and an anhydride is preferably performed at around 50°C. To overcome this problem, a high-pressure autoclave was used to prevent loss of acetaldehyde at elevated temperatures. A one-pot reaction was therefore performed in the autoclave using the reactants, acetaldehyde, formamide and succinic anhydride.

[0069] In the studies, 1.25g succinic anhydride (10mmol), 0.5ml formamide (13mmol), 0.035ml triethylamine (0.25mmol) and 10ml acetaldehyde (175mmol) were added to the autoclave which was sealed and placed in an oil bath at 50°C. The reaction was stirred for 4h and then the pressure (excess acetaldehyde) was released. The autoclave was then cooled to room temperature. A pale yellow liquid was collected. Upon partial evaporation of remaining acetaldehyde a white solid precipitated was separated. Further product was collected from the remaining liquid solution by careful evaporation and washing with acetaldehyde. NMR analysis demonstrated formation of the HEF adduct.

[0070] **Example 8. Preparation of tethered anhydride**

[0071] i) As illustrated in Scheme 1 below, Allylsuccinic anhydride [0.67g; 0.005mol], (3-mercaptopropyl-trimethoxysilane [2.8g; 0.014mol] and AIBN [50mg] were dissolved in chloroform [60ml] and refluxed overnight. Solid product was filtered off, and the solvent was removed from the filtrate to leave a yellow oil.

[0072] ii) The product from i) was added to a stirred suspension of silica gel [8g; surface area ~500m<sup>2</sup>/g] in toluene [200ml] and stirring was continued at room temperature for approximately 20h. The silica (i.e. tethered anhydride) was then filtered off and washed with toluene.



Scheme 1

[0073] The foregoing description and accompanying drawings set forth the preferred embodiments of the invention at the present time. Various modifications, additions and alternative designs will, of course, become apparent to those skilled in the art in light of the foregoing teachings without departing from the scope of the invention. The scope of the invention is indicated by the following claims rather than by the foregoing description. All changes and variations that fall within the meaning and range of equivalency of the claims are to be embraced within their scope.